Lepton flavor violating Higgs boson decays in the MSSM-seesaw

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Lepton flavor violating Higgs boson decays (LFVHD) are studied in the context of the Minimal Supersymmetric Standard Model (MSSM) enlarged with three right handed neutrinos and their supersymmetric partners, and with the neutrino masses being generated by the seesaw mechanism. We compute the partial widths for these decays to one-loop order and analyze numerically the corresponding branching ratios in terms of the MSSM and seesaw parameters. We analyze in parallel the lepton flavor changing $l_j \to l_i\gamma$ decays and explore the maximum predicted rates for LFVHD, mainly for $H^0, A^0 \to \tau\bar{\mu}$ decays, by requiring compatibility with neutrino and $BR(l_j \to l_i\gamma)$ data. We find LFVHD ratios of up to 10^{-5} in some regions of the MSSM-seesaw parameter space.

1 Introduction

The observed neutrino masses do require a theoretical framework beyond the Standard Model of Particle Physics with just three massless left-handed neutrinos. Within the MSSM-seesaw context, which will be adopted here, the MSSM particle content is enlarged by three right handed neutrinos plus their corresponding supersymmetric (SUSY) partners, and the neutrino masses are generated by the seesaw mechanism. Three of the six resulting Majorana neutrinos have light masses, $m_{\nu_i}, i = 1, 2, 3$, and the other three have heavy masses, $m_{N_i}, i = 1, 2, 3$. These physical masses are related to the Dirac mass matrix m_D, the right-handed neutrino mass matrix m_M, and the unitary matrix U_{MNS} by $diag(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) \simeq U^T_{MNS}(-m_D m_M^{-1} m_D^T)U_{MNS}$ and $diag(m_{N_1}, m_{N_2}, m_{N_3}) \simeq m_M$, respectively. Here we have chosen an electroweak eigenstate basis where m_M and the charged lepton mass matrix are flavor diagonal, and we have assumed that all elements in $m_D = Y_\nu < H_2 >$, where Y_ν is the neutrino Yukawa coupling matrix and $< H_2 >= v \sin\beta$ ($v = 174$ GeV), are much smaller than those of m_M. The two previous relations can be rewritten together in a more convenient form for the work presented here as, $m_D^T = i m_N^{diag\,1/2} R m_\nu^{diag\,1/2} U^+_{MNS}$, where R is a general complex and orthogonal 3×3 matrix, which will be parameterized by three complex angles θ_i, $i = 1, 2, 3$.

One of the most interesting features of the MSSM-seesaw model is the associated rich phenomenology due to the occurrence of lepton flavor violating (LFV) processes. Whereas in the standard (non-SUSY) seesaw models the ratios of LFV processes are small due to the smallness of the light neutrino masses, in the SUSY-seesaw models these can be large due to an important additional source of lepton flavor mixing in the soft-SUSY-breaking terms. Even in the scenarios with universal soft-SUSY-breaking parameters at the large energy scale associated to the SUSY breaking M_X, the running from this scale down to m_M induces, via the

neutrino Yukawa couplings, large lepton flavor mixing in the slepton soft masses, and provides the so-called slepton-lepton misalignment, which in turn generates non-diagonal lepton flavor interactions. These interactions can induce sizable ratios in several LFV processes with SM charged leptons in the external legs, which are actually being tested experimentally with high precision and therefore provide a very interesting window to look for indirect SUSY signals. They can also induce important contributions to other LFV processes that could be meassured in the next generation colliders, as it is the case of the MSSM Higgs boson decays into $\tau\bar{\mu}$, $\tau\bar{e}$ and $\mu\bar{e}$ which are the subject of our interest.

Here we compute the partial widths for these lepton flavor violating Higgs boson decays (LFVHD) to one-loop order and analyze numerically the corresponding branching ratios in terms of the MSSM and seesaw parameters, namely, M_0, $M_{1/2}$, $\tan\beta$, m_{N_i} and R. We analyze in parallel the lepton flavor changing $l_j \to l_i\gamma$ $(i \neq j)$ decays and explore the maximum predicted rates for LFVHD, mainly for $H^0, A^0 \to \tau\bar{\mu}$ decays, by requiring compatibility with $BR(l_j \to l_i\gamma)$ data. For these we use the present experimental upper bounds given by [1] $|BR(\mu \to e\gamma)| < 1.2 \times 10^{-11}$, $|BR(\tau \to \mu\gamma)| < 3.1 \times 10^{-7}$ and $|BR(\tau \to e\gamma)| < 2.7 \times 10^{-6}$.

For the numerical analysis we choose, $M_X = 2 \times 10^{16}$ GeV and $A_0 = 0$. The U_{MNS} matrix elements and the m_{ν_i} are fixed to the most favored values by neutrino data [2] with $\sqrt{\Delta m^2_{sol}} = 0.008$ eV, $\sqrt{\Delta m^2_{atm}} = 0.05$ eV, $\theta_{12} = \theta_{sol} = 30^o$, $\theta_{23} = \theta_{atm} = 45^o$, $\theta_{13} = 0^o$ and $\delta = \alpha = \beta = 0$. We consider two plaussible scenarios, one with quasi-degenerate light and degenerate heavy neutrinos and with $m_{\nu_1} = 0.2\,eV\,, m_{\nu_2} = m_{\nu_1} + \frac{\Delta m^2_{sol}}{2m_{\nu_1}}\,, m_{\nu_3} = m_{\nu_1} + \frac{\Delta m^2_{atm}}{2m_{\nu_1}}$ and $m_{N_1} = m_{N_2} = m_{N_3} = m_N$; and the other one with hierarchical light and hierarchical heavy neutrinos, and with $m_{\nu_1} \simeq 0\,eV\,, m_{\nu_2} = \sqrt{\Delta m^2_{sol}}\,, m_{\nu_3} = \sqrt{\Delta m^2_{atm}}$ and $m_{N_1} \leq m_{N_2} < m_{N_3}$.

This is a reduced version of our more complete work [3] to which we address the reader for more details.

2 Numerical results and conclusions

We show in figs. (1) through (4) the numerical results for the branching ratios of the LFVHD together with the branching ratios for the relevant $l_j \to l_i\gamma$ decays. The results of $BR(H_0 \to \tau\bar{\mu})$ as a function of m_N, for degenerate heavy neutrinos and real R, are illustrated in fig. (1a), for several $\tan\beta$ values, $\tan\beta = 3, 10, 30, 50$. Notice that in this case, the rates do not depend on R. The explored range in m_N is from 10^8 GeV up to 10^{14} GeV which is favorable for baryogenesis. We also show in this figure, the corresponding predicted rates for the most relevant lepton decay, which in this case is $\mu \to e\gamma$, and include its upper experimental bound. We have checked that the other lepton decay channels are well within their experimental allowed range. The ratios for A_0 decays, not shown here for brevity, are very similar to those for H_0 decays in all the studied scenarios in this work. We have also found that the ratios for the light Higgs boson, h_0, behave very similarly with m_N and $\tan\beta$ but are smaller than the heavy Higgs ones in about two orders of magnitude. ¿From our results we learn about the high sensitivity to $\tan\beta$ of the LFVHD rates for all Higgs bosons which, at large $\tan\beta$, scale roughly as $(\tan\beta)^4$, in comparison with the lepton decay rates which scale as $(\tan\beta)^2$. The dependence of both rates on m_N is that expected from the mass insertion approximation, where $BR(H_x \to l_j\bar{l}_i)$, $BR(l_j \to l_i\gamma) \propto |m_N \log(m_N)|^2$. We find that the largest ratios, which are for H_0 and A_0, are in any case very small, at most 10^{-10} in the region of high $\tan\beta$ and high m_N. Besides, the rates for $\mu \to e\gamma$ decays are below the upper experimental bound for all explored $\tan\beta$ and m_N values. The branching ratios for the Higgs boson decays into $\tau\bar{e}$ and $\mu\bar{e}$ are much smaller than the $\tau\bar{\mu}$ ones, as expected, and we do not show plots for them. For instance, for $m_N = 10^{14}$ GeV, and $\tan\beta = 50$ we find $BR(H^{(x)} \to \tau\bar{\mu})/BR(H^{(x)} \to \tau\bar{e}) = 4 \times 10^3$ and $BR(H^{(x)} \to \tau\bar{\mu})/BR(H^{(x)} \to \mu\bar{e}) = 1.2 \times 10^6$ for the three Higgs bosons.

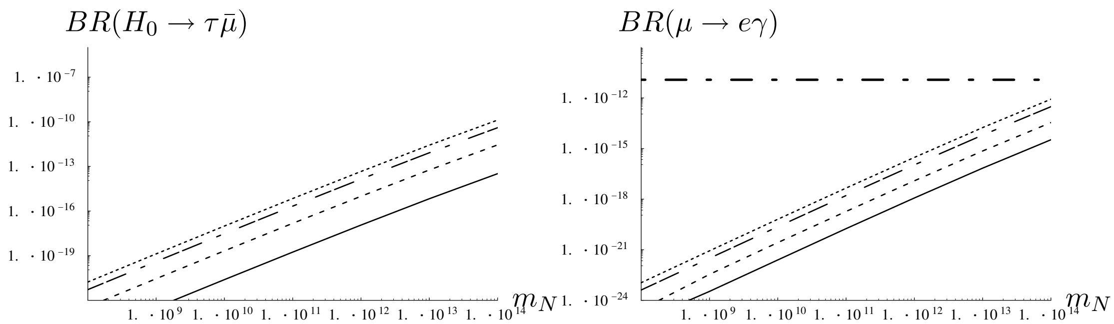

Figure 1: Dependence of LFV ratios with m_N (GeV) for degenerate heavy neutrinos and real R and for several values of $\tan\beta$. **(1a)** $BR(H_0 \to \tau\bar{\mu})$. **(1b)** $BR(\mu \to e\gamma)$. The horizontal line is the experimental upper bound. In both plots, the solid, dashed, dashed-dotted and dotted lines are the preditions for $\tan\beta = 3, 10, 30$ and 50, respectively, and $M_0 = 400$ GeV, $M_{1/2} = 300$ GeV.

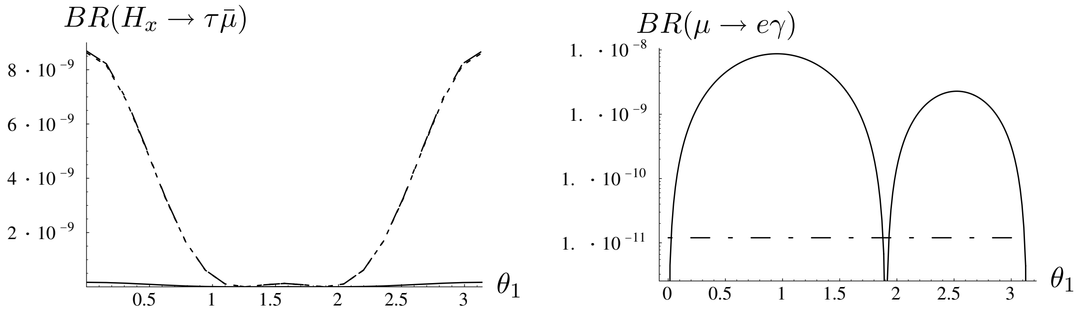

Figure 2: LFV ratios for hierarchical heavy neutrinos and real R with $\theta_1 \neq 0$, $\theta_2 = \theta_3 = 0$ and $(m_{N_1}, m_{N_2}, m_{N_3}) = (10^8, 2\times 10^8, 10^{14})$ GeV. Here, $\tan\beta = 50$, $M_0 = 400$ GeV and $M_{1/2} = 300$ GeV. **(2a)** $BR(H_x \to \tau\bar{\mu})$. Solid, dashed and dashed-dotted lines (the two later undistinguishible here and in all plots) correspond to $H_x = (h_0, H_0, A_0)$ respectively. **(2b)** $BR(\mu \to e\gamma)$. The horizontal line is the experimental upper bound.

The case of hierarchical neutrinos gives clearly larger LFV rates than the degenerate case, as can be seen in figs. (2), (3) and (4). However, we will get restrictions on the maximum allowed Higgs decay rates coming from the experimental lepton decay bounds. For instance, the case of real θ_1, that is illustrated in fig. (2) shows that compatibility with $\mu \to e\gamma$ data occurs only in the very narrow deeps at around $\theta_1 = 0$, 1.9 and π. Notice that it is precisely at the points $\theta_1 = 0, \pi$ where the $BR(H_0, A_0 \to \tau\bar{\mu})$ rates reach their maximum values, although these are not large, just about 10^{-8}. We have checked that for lower $\tan\beta$ values, the allowed regions in θ_1 widen and are placed at the same points, but the corresponding maximum values of the LFVHD rates get considerably reduced. For the alternative case, not shown here, of real $\theta_2 \neq 0$, with $\theta_1 = \theta_3 = 0$ we get a similar behaviour of $BR(H_x \to \tau\bar{\mu})$ with θ_2 than with θ_1, and the maximum values of about 10^{-8} are now placed at $\theta_2 = 0$, π. In contrast, $BR(\mu \to e\gamma)$ is constant with θ_2 and reach very small values, well below the experimental bound. In particular, for $\tan\beta = 50$, $M_0 = 400$ GeV and $M_{1/2} = 300$ GeV it is 10^{-19}. Regarding the dependence with θ_3, not shown here either, a reverse situation is found, where $BR(H_x \to \tau\bar{\mu})$ is approximately constant and, for the heavy Higgs bosons, it is around 10^{-8}. On the contrary, $BR(\mu \to e\gamma)$ varies but it is always well below the experimental upper bound. In addition, we have checked that the $BR(\tau \to \mu\gamma)$ and $BR(\tau \to e\gamma)$ rates are within the experimental allowed range in all cases. In conclusion, for real R we find that the maximum allowed LFVHD rates are at or below 10^{-8}. The case of complex R is certainly more promissing. The examples illustrated in figs. (3) and (4) are for the most favorable case, among the ones studied here, of complex $\theta_2 \neq 0$

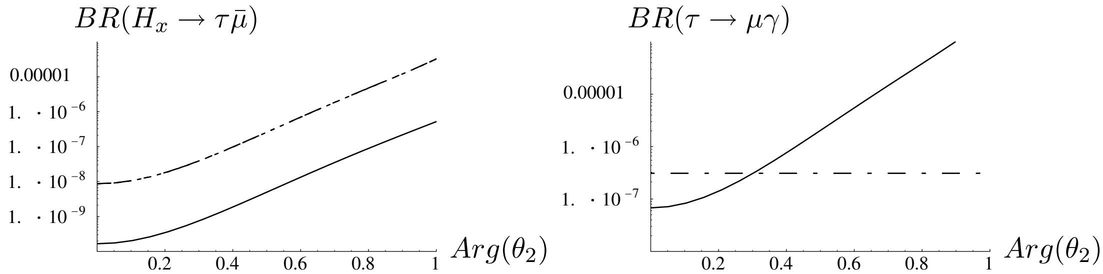

Figure 3: LFV ratios for hierarchical heavy neutrinos and complex R with $\theta_2 \neq 0$, $\theta_1 = \theta_3 = 0$, and $(m_{N_1}, m_{N_2}, m_{N_3}) = (10^8, 2\times 10^8, 10^{14})$ GeV. Here, $\tan\beta = 50$, $M_0 = 400$ GeV, and $M_{1/2} = 300$ GeV. **(3a)** Dependence of $BR(H_x \to \tau\bar{\mu})$ with $Arg(\theta_2)$ for $|\theta_2| = \pi$. Solid, dashed and dashed-dotted lines are for $H_x = (h_0, H_0, A_0)$ respectively. **(3b)** Same as (3a) but for $BR(\tau \to \mu\gamma)$. The horizontal line is the experimental upper bound.

with $\theta_1 = \theta_3 = 0$ and show that considerably larger $BR(H_x \to \tau\bar{\mu})$ rates than in the real R case are found. Regarding the dependence with θ_2, we find that for the explored values with $(|\theta_2|, Arg(\theta_2)) \leq (3.5, 1)$, the Higgs rates grow with both $|\theta_2|$ and $Arg(\theta_2)$ and, for the selected values of the MSSM-seesaw parameters in fig. (3), they reach values up to around 5×10^{-5}. We have checked that the predicted rates for $BR(\mu \to e\gamma)$ are well below the experimental upper bound, being nearly constant with θ_2 and around 10^{-19}. Similarly, for the $\tau \to e\gamma$ decay. Notice that the smallness of these two decays, in the case under study of $\theta_2 \neq 0$, is not maintained if our hypothesis on $\theta_{13} = 0$ is changed. For instance, for $\theta_{13} = 5^o$, which is also allowed by neutrino data, we get $BR(\mu \to e\gamma) \sim 1.8 \times 10^{-8}$ well above the experimental upper bound. Therefore, in this case of complex $\theta_2 \neq 0$, the relevant lepton decay is $\tau \to \mu\gamma$ which is illustrated in figs. (3) and (4) together with its experimental bound. For the set of parameters chosen in fig. (3), we get that the allowed region by $\tau \to \mu\gamma$ data of the $(|\theta_2|, Arg(\theta_2))$ parameter space implies a reduction in the Higgs rates, leading to a maximum allowed value of just 5×10^{-8}. The dependence of the LFV ratios with M_0 and $M_{1/2}$ for hierarchical neutrinos are shown in fig. (4). We see clearly the different behaviour of the LFVHD and the lepton decays with these parameters, showing the first ones a milder dependence. This implies, that for large enough values of M_0 or $M_{1/2}$ or both the $BR(\tau \to \mu\gamma)$ rates get considerably suppresed, due to the decoupling of the heavy SUSY particles in the loops, and enter into the allowed region by data, whereas the $BR(H_0 \to \tau\bar{\mu})$ rates are not much reduced. In fact, we see in figs. (4e) and (4f) that for the choice $M_0 = M_{1/2}$ the τ decay ratio crosses down the upper experimental bound at around $M_0 = 1100$ GeV whereas the Higgs decay ratio is still quite large $\sim 4 \times 10^{-6}$ in the high M_0 region, around $M_0 \simeq 2000$ GeV. This behaviour is a clear indication that the heavy SUSY particles in the loops do not decouple in the LFVHD. Notice also that it can be reformulated as non-decoupling in the effective $H^{(x)}\tau\mu$ couplings and these in turn can induce large contributions to other LFV processes that are mediated by Higgs exchange as, for instance, $\tau \to \mu\mu\mu$. However, we have checked that for the explored values in this work of M_0, $M_{1/2}$, $\tan\beta$, R and m_{N_i} that lead to the anounced LFVHD ratios of about 4×10^{-6}, the corresponding $BR(\tau \to \mu\mu\mu)$ rates are below the present experimental upper bound.

In summary, after exploring the dependence of the LFVHD rates with all the involved MSSM-seesaw parameters, and by requiring compatibility with data of the correlated predictions for $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ decays, we find that $BR(H_0, A_0 \to \tau\bar{\mu})$ as large as 10^{-5}, for hierarchical neutrinos and large M_{SUSY} in the TeV range can be reached. These rates are close but still below the expected future experimental reach of about 10^{-4} at the LHC and next generation linear colliders.

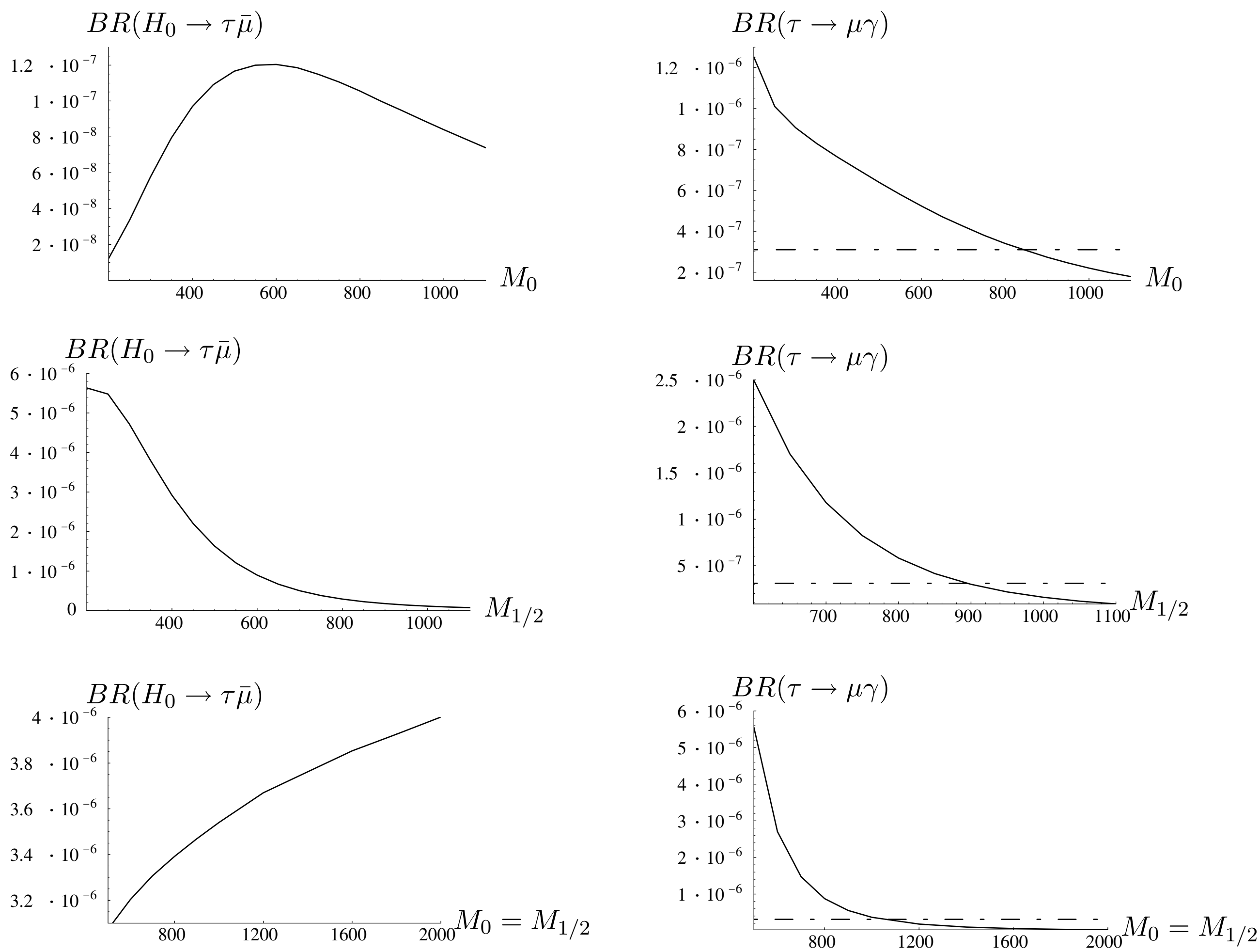

Figure 4: Dependence with M_0 (GeV) and $M_{1/2}$ (GeV) for $(m_{N_1}, m_{N_2}, m_{N_3}) = (10^8, 2 \times 10^8, 10^{14})$ GeV, $\theta_1 = \theta_3 = 0$ and $\tan\beta = 50$. **(4a)** $BR(H_0 \to \tau\bar{\mu})$ versus $M_0(GeV)$ for $M_{1/2} = 300$ GeV and $\theta_2 = \pi e^{0.4i}$. **(4b)** Same as (4a) but for $BR(\tau \to \mu\gamma)$. **(4c)** $BR(H_0 \to \tau\bar{\mu})$ versus $M_{1/2}(GeV)$ for $M_0 = 400$ GeV and $\theta_2 = \pi e^{0.8i}$. **(4d)** Same as (4c) but for $BR(\tau \to \mu\gamma)$. **(4e)** $BR(H_0 \to \tau\bar{\mu})$ versus $M_0 = M_{1/2}(GeV)$ for $\theta_2 = \pi e^{0.8i}$. **(4f)** Same as (4e) but for $BR(\tau \to \mu\gamma)$. The horizontal lines are the upper experimental bound on $BR(\tau \to \mu\gamma)$.

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References

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